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Globalisation and environmental pressure in Europe: evidence from ecological footprint dynamics

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Abstract

Background Environmental degradation, as assessed by the ecological footprint, remains a significant global challenge. Although research has examined its linkages with globalisation, evidence remains fragmented and region-specific, thereby leaving uncertainties regarding global patterns and temporal causality.

Methods This study examines the predictive causal dynamics based on Granger causality between globalisation and environmental degradation across 35 European countries from 1993 to 2023, using the panel and country-level Granger causality and Wavelet Coherence analyses. Given the strong regulatory architecture of the European Union, understanding how global economic integration interacts with environmental outcomes is crucial for designing effective regional environmental governance strategies.

Results The findings demonstrate that environmental-globalisation dynamics in Europe operate through multi-scale interaction rather than uniform country-level pathways. These findings highlight the importance of supranational regulatory coordination within the European Union, where environmental governance is shaped not only by national policies but also by regional regulatory frameworks. Furthermore, the study's findings underscore the importance of regional and country-specific policy implications. These patterns suggest potential heterogeneity across countries; however, given the statistical limitations associated with multiple testing and the small sample size. These findings should be interpreted as indicative rather than conclusive evidence of institutional differences. Time–frequency analysis reveals that globalisation intensifies ecological pressure in the short-term, while it demonstrates mitigating effects over the medium-term. This pattern is consistently observed across the empirical analysis.

Conclusion By employing the ecological footprint as a comprehensive indicator and introducing the LJC heat map visualisation, this study advances methodological and empirical understanding of the globalisation-environmental nexus, while providing targeted policy insights for SDG-aligned sustainability strategies.

Keywords Ecological footprint, Environmental degradation, Europe, Globalisation, SDG, Wavelet coherence

Introduction

Environmental degradation and globalisation European challenge

Europe represents one of the most environmentally regulated regions globally. However, it remains among the world's largest contributors to the ecological footprint due to its high consumption intensity and global production and outsourcing [1]. Through initiatives such as the

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European Green Deal, carbon pricing mechanisms, and stringent environmental directives, the European Union has developed one of the most comprehensive environmental regulatory systems worldwide. Globalisation is a key driver of economic expansion, negatively impacting environmental sustainability by degrading the environment [2, 3]. Europe faces a policy dilemma: how to sustain global economic integration while limiting ecological pressure. This challenge is particularly relevant within the European Union, where economic integration policies must operate alongside environmental protection frameworks aimed at achieving climate neutrality and sustainable resource management. This study investigates how environmental degradation and globalisation are interconnected across the European region and provides insights into policies to protect the ecosystem. Despite extensive empirical research, it remains unclear whether environmental degradation in Europe is driven primarily by national characteristics or broader globalisation dynamics within a highly integrated regional context.

Brief literature and positioning

Previous studies based on Europe have shown that globalisation contributes to environmental degradation, both positively and negatively [4, 5]. Moreover, further analysis examines directional causalities between Europe's environment and globalisation [3, 6], yielding mixed findings for Europe.

Research gap and motivation

Despite the growing literature on the nexus between environmental degradation and globalisation in Europe, several important gaps persist. Notwithstanding extensive European evidence, the causal direction and time frequency dynamics between globalisation and comprehensive environmental degradation remain unresolved, particularly when accounting for regional dominance and country-level heterogeneity.

Moreover, previous studies have predominantly focused on individual metrics such as carbon dioxide (CO_2) emissions, greenhouse gas (GHG) emissions, and air pollution, rather than engaging composite measures to comprehensively assess environmental degradation. Methodologically, many studies have relied on Autoregressive Distributed Lag, Fully Modified Ordinary Least Squares, and panel regression techniques; these methods offer limited insight into the causality and directionality of relationships between variables. Empirically, although investigations have examined the correlation between environmental degradation and globalisation within Europe, country-specific analyses remain scarce.

Unlike single indicators such as CO_2 emissions which capture only one dimension of environmental degradation, the ecological footprint provides a comprehensive measure of environmental pressure by incorporating multiple components, including carbon absorption, land use, and resource consumption. This allows for a more holistic assessment of sustainability and enables a broader understanding of the environmental implications of globalisation.

It is important to note that Granger causality identifies predictive relationships rather than structural causal mechanisms. In the European context, globalisation and environmental pressure are jointly influenced by common macroeconomic, institutional, and energy related factors. Therefore, the empirical findings should be integrated as indicative of dynamic interdependencies rather than direct causal transmission effects.

Contribution of the study

This study makes three main contributions. First, it utilises ecological footprint consumption data, which provides a comprehensive view of the environmental impact. Second, the research establishes causal direction rather than the association between globalisation and ecological footprint in Europe and its selected nations, utilising the Granger causality approach. The regional analysis is further expanded using the Wavelet Coherence approach to allow insights into time, frequency, and correlation effects observed within the causal nexuses. Finally, this analysis provides policy insights for European countries aligning with the 2030 Agenda for Sustainable Development, to achieve sustainable development, while reducing environmental degradation and enhancing global integration. Collectively, these studies suggest that globalisation's environmental effects are conditional rather than universal, varying with time, institutional quality, and economic structure. However, the lack of multi-scale causal analysis renders these mechanisms insufficiently understood.

By combining a comprehensive environmental indicator with multi-scale analytical techniques, this study contributes to the literature by demonstrating that environmental-globalisation dynamics in Europe are predominantly driven by regional level processes, rather than isolated national mechanisms.

Structure of the paper

The remainder of this paper is structured to include a critical analysis of existing studies related to the environmental degradation-globalisation nexus in Europe, the data and methodologies used, the study's findings, their discussion, and policy recommendations developed accordingly.

Literature review

The following section details the process of literature search, a critical analysis of the existing state of empirical studies and the research gaps identified and explained in relation to the current study.

Literature search flow

The analysis of the existing literature to identify the prominent keywords related to the study is illustrated in Fig. 1. The literature search process presented in Additional file 1 details the referred databases, the keywords used, and the number of articles observed and included.

Definition of key concepts

The ecological footprint (EFP) is defined as the level of land and water required to produce the resources consumed and to absorb the waste generated by individuals, countries, or regions [7]. The objective of this concept is to compare the ecological footprint of all human activities with the Earth's biocapacity [8]. Accordingly, the world's most populous nations are observed to have the most severe levels of environmental degradation [9]. The ecological footprint is a comprehensive indicator of sustainable development that encompasses all aspects of a region's environmental data. Most prior studies rely on CO_2 emissions as a proxy for environmental degradation. However, such measures may underestimate broader ecological pressures, which are more comprehensively captured by the ecological footprint. To overcome these constraints, this study uses the ecological footprint as a more comprehensive and multifaceted indicator of environmental degradation than prior studies.

The process of growing economic, political, and social integration and interdependence of nations and regions [3], and the relationship between individuals, nations, and governments, along with the exchange of concepts and information, is defined as globalisation [10]. It plays a significant role in boosting economic growth, also affecting environmental sustainability through increased trade and resource consumption. Globalisation (GLO) also presents opportunities to improve sustainability through innovative and systematic production methods [11, 12]. Being a multifaceted phenomenon, globalisation is often recognised as a complex concept whose influence varies by context.

Environmental degradation and globalisation nexus: evidence from Europe

The impact of globalisation on environmental degradation has been investigated by numerous studies, although the theoretical foundations of these findings remain dispersed and inconsistent. Globalisation and environmental degradation nexus identifies contradictory findings in Europe over the long-term and short run [10, 13–16].

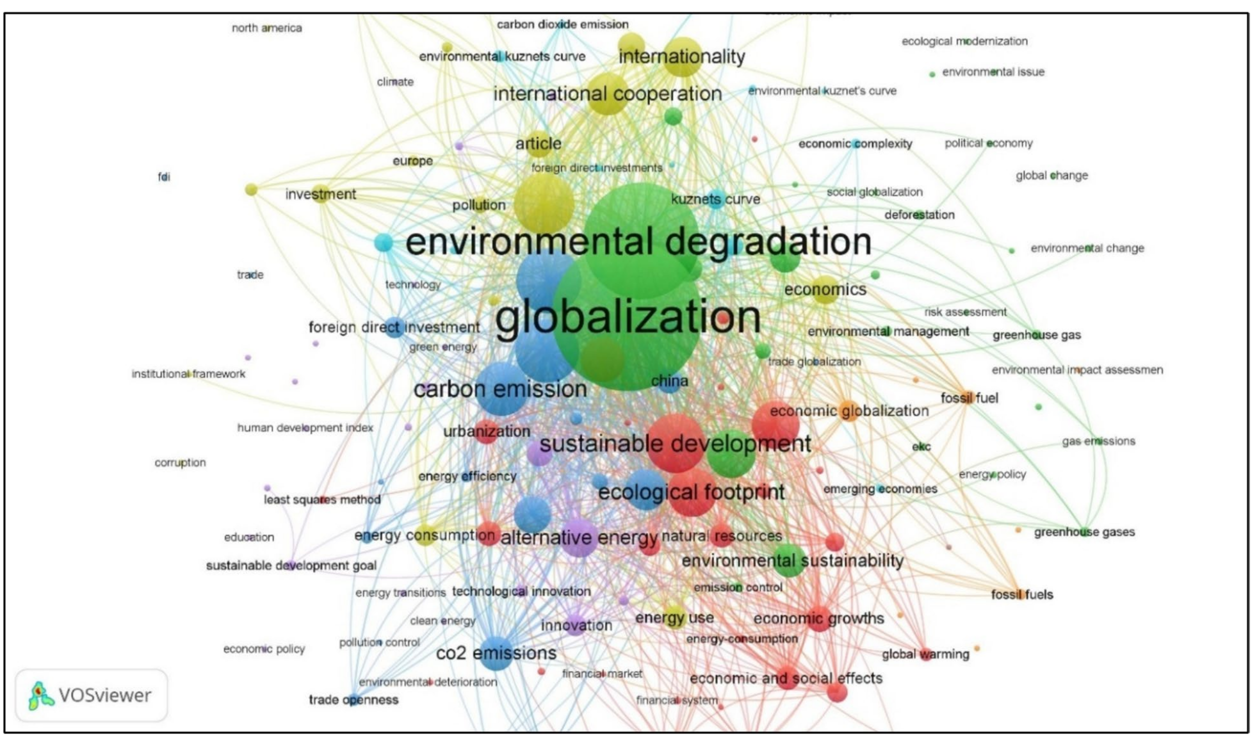


Fig. 1 Literature search keyword analysis. *Source*: Authors' illustration

A similar temporal shift was also observed in the region between CO_2 and globalisation during the pre-2000 and post-2000 period [17]. The mixed short- and long-term findings can be explained by the Environmental Kuznets curve (EKC) and ecological modernisation theory (EMT), which emphasise structural transformation and sustainable innovation. Most studies had used static panel models, which may not account for differences between units or how variables change over time. These methodological approaches often overlook the role of regulatory frameworks, which can influence how globalisation affects environmental outcomes across countries. However, prior studies have identified inconsistent short- and long-term effects of globalisation and environmental degradation, with temporal variations across the European region, while the current study provides a holistic view of the variables by providing short, long and medium-term correlations in a specific time frequency.

When these studies provide valuable insight, they fail to jointly examine the causal relationship between GLO and environmental degradation [18–20] in this heavily industrialised region. A bidirectional causal nexus was observed between EFP and globalisation [21, 22], implying that global integration amplifies regional resource consumption, whereas treaties and policies ensure sustainable resource use thus shaping the nature of that integration. Individually, the economic, social, and political dimensions of globalisation were observed to exhibit mixed causal relationships with EFP [3]. Most prior studies rely on panel and regression methods to provide relationships and correlations between variables in the short and long run. However, most previous investigations have established a directional causal link between globalisation and environmental degradation, indicating that highly globalised countries experience greater environmental degradation. The current study comprehensively explains how environmental damage resulting from global economic integration will be driven by factors such as high levels of pollution, resource consumption, and emissions associated with global trade liberalisation.

Although the connection between globalisation and environmental degradation has been extensively examined in previous studies, the theoretical justifications are still limited and insufficiently integrated. Although identified as having a relatively minor impact on EFP [5], sustainable environmental quality in Europe is found to be negatively affected by greater degrees of globalisation [23, 24]. Economic integration worsens EFP, with trade globalisation and energy consumption being key components of total production footprint [2, 12]. Despite this, developed and industrialised European nations have also been able to achieve lower levels of environmental degradation by shifting their industrial bases to developing regions. This has thus amplified environmental decline in underdeveloped nations [25]. The EKC and ecological modernisation theory explain how GLO has a mixed effect on environmental degradation, increasing damage through industrial development at first, and reducing it through institutional capacity and technological transfer. Despite strategic policy and regulatory measures to control the extent of environmental damage and to establish environmental quality in the region, Europe is still struggling with biodiversity loss. This, in turn, highlights the necessity of appropriate policy mechanisms to establish European protection and environmental sustainability.

Environmental degradation and globalisation nexus: cross-country analysis

Existing scholarly studies have investigated the relationship between the ecological footprint and globalisation in European nations; however, findings remain inconclusive. Existing studies have shown that GLO increases EFP in European countries in the long run, while several studies have found mixed positive and negative impacts between EFP and GLO [8, 22, 26]. These numerous findings can be explained by the EKC theory, which posits that economic expansion driven by globalisation can affect the environment in the short- and long-term. However, most studies based on regression econometric models overlook directional causality between these variables, leaving the significance of conducting a causality analysis to investigate how EFP and GLO are mutually associated across European nations.

Previous studies have investigated directional causality between EFP and GLO within European countries and aimed to find diverse findings. Several studies revealed bidirectional relationships between EFP and GLO in European countries, including the G20 and BRICS nations, although a certain number of studies based on the G7 and developed economies found that in most European countries' GLO causes the EFP [4, 6, 27–30]. However, limited studies investigate directional causality across countries, yielding heterogeneous findings and warranting broader investigation to advance the existing literature by providing country-specific predictive causal dynamics based on Granger causality.

Recent studies highlight the role of artificial intelligence in improving environmental efficiency and supporting renewable energy transitions [31–33]. However, these studies primarily focus on technological mechanism, whereas the role of broader globalisation dynamic remains less explored. Furthermore, Additional file 2 gives a more comprehensive analysis of the literature.

Research gap reformation

Although several studies have examined the directional relationship between globalisation and environmental degradation, important research gaps remain. In contrast to common indicators such as CO_2 emissions, GHG emissions, and air pollution, this study used the ecological footprint as a comprehensive proxy for environmental degradation, which encompasses six fundamental components. By accounting for the biologically productive land and water areas needed to support human activity, the ecological footprint offers a more comprehensive assessment of environmental pressure. To investigate long-term correlations between variables, most of the previous research has used regression-based analytical methods. This study employed two main methodological techniques, the Wavelet Coherence and Granger causality analyses, to examine time–frequency-based correlations and directional causal linkages between variables. Furthermore, several studies have investigated the relationship between these variables across regions and income groups, but few have conducted country-specific analyses.

The existing literature present mixed and often contradictory findings regarding the relationship between globalisation and environmental degradation. While some studies support the Environmental Kuznets curve hypothesis by suggesting that the environmental pressure initially increases and then declines with development, others highlight the role of institutional and technological factors emphasised by ecological modernisation theory. These conflicting findings indicate that the globalisation-environmental nexus is complex and may vary across time scales and institutional contexts. This study addresses this gap by adapting a multi-scale analytical framework to capture both short-term dynamics and broader systematic patterns.

Theoretical framework

Environmental Kuznets curve (EKC) perspective

While many studies seek to verify this concept using various environmental degradation indicators, a significant portion examine the importance of factors other than wealth in causing an EKC pattern [34, 35]. These variables include international trade, income distribution and equity, structural changes, technological and energy-efficiency advancements, institutional framework and governance, and lastly, consumer preferences [36]. A potential EKC pattern may be sufficiently or partially explained by the significance of these reasons. Additionally, the EKC suggests a non-linear relationship between increasing national economic development and environmental degradation [12], demonstrating that while globalisation has detrimental short-term environmental effects, full economic growth can result in better environmental quality as nations reach a certain income level and embrace green innovations.

Ecological modernisation theory

Ecological modernisation theory contends that, rather than drastically altering society, environmental issues may be resolved within the current capitalist system through technological advancement, market incentives, economic restructuring and governmental regulations that support eco-efficiency and green growth [37]. Within the European context, this theoretical perspective is closely linked to environmental governance mechanisms, where regulatory policies and institutional innovation promote sustainable technological transitions. Therefore, by applying the EKC and ecological modernisation theories to link globalisation and environmental degradation, this study examines whether the considered variables accelerate countries' progress towards the EKC turning point. Ecological modernisation theory promotes the use of institutional innovation, policy tools, and technological advances to achieve ecological sustainability alongside economic growth [38]. Ecological modernisation theory offers businesses a theoretical framework for utilising modern technology to enhance their environmental performance.

Theoretical expectations and hypotheses

From a theoretical perspective, the EKC framework suggests that globalisation may initially increase environmental pressure through scale effects, while later contributing to environmental improvements via technological advancement and regulatory improvements. In contrast, EMT emphasises the role of institutional coordination, technological innovation and policy integration in reducing environmental degradation. Accordingly, this study expects that the relationship between globalisation and ecological footprint may exhibit dynamic and context dependent patterns reflecting both short-term pressures and long-term sustainability transitions.

Based on findings from previous EKC theory literature, globalisation is expected to increase environmental degradation in the short-term, and, in the long-term, to decrease it. EMT theory suggests that globalisation can not only worsen the environment but also improve it. This study tests whether globalisation produces short run environmental degradation, but also long run ecological improvement as predicted by EKC and ecological modernisation theory.

The study accordingly analyses the globalisation-environmental degradation nexus at both European regional and cross-country contexts. The hypotheses developed at the regional level are as follows.

H_1: Globalisation Granger causes environmental degradation in Europe

H_2: Environmental degradation Granger causes globalisation in Europe

According to $H_{1,}$ globalisation has a significant effect on environmental degradation while according to $H_{2,}$ environmental degradation has a significant effect on globalisation at the regional level.

For the country-wise analysis, stated below are the null and alternative hypotheses to determine whether any directional predictability exists between variables at the country-level.

H_1: Globalisation Granger causes environmental degradation within countries

H_2: Environmental degradation Granger causes globalisation within countries

According to $H_{1,}$ globalisation has a significant effect on environmental degradation while according to $H_{2,}$ environmental degradation has a significant effect on globalisation at the country-level.

Data and methodology

The following section will provide a detailed description of the variables and measures, their data sources, and the econometric strategies applied.

Data and variables

This study covers the 31-year period from 1993 to 2023 and includes 35 countries classified as a part of the European region by Our World in Data. The sample was constructed based on data availability and consistency across all variables, with countries exhibiting substantial missing observations over the study period excluded to ensure robustness in panel estimation. Furthermore, the relatively short time dimension (31 annual observations per country) may limit statistical power and increase sensitivity to lag selection, potentially affecting the stability of country-level results.

Environmental degradation and globalisation are the key variables used in this study. As a measure of environmental degradation, this study applies the ecological footprint consumption [Global Hectares (Gha) per capita] data retrieved from the Global Footprint Network. To measure globalisation, the KOF Globalisation Index sourced from the KOF Swiss Economic is utilised. Although the Europe context is characterised by strong regional integration, the empirical analysis in this study focuses especially on the aggregate KOF Globalisation Index, rather than a direct measure of the regional integration. This study utilised the most recent data releases (2025 editions) for both EFP and GLO for the analytical purpose. A summary of key variables, their measures, and the data sources are provided in the Table 1. A detailed dataset description in is provided in Additional file 3.

Econometric strategy overview

The econometric strategies will provide a comprehensive explanation about unit root tests, stability tests, panel and country-wise Granger test, Wavelet Coherence analysis and LJC heat map.

Unit root test

Examination of the variables' stationarity is a crucial step before moving on to Granger causality analysis. Stationarity of a variable refers to the variable's statistical properties being consistent within the studied time period [39]. This study applied two-unit root tests, namely the Levin–Lin–Chu (LLC) and Dickey–Fuller (DF) tests, to assess the stationarity of variables across the region and nations.

The LLC test is used to assess the stationarity requirement for the regional stationarity test [40]. This technique is widely used in previous scholarly studies to evaluate the stationarity within a panel [41, 42]. During the LLC test, the null hypothesis considers the panel is non-stationary, and the alternative hypothesis that the panel is stationary. Equation 1 represents a mathematical representation of the general LLC equation, where the intercept is denoted by θ_0, the autoregressive coefficient

Table 1 Variables and data sources

Variable	Definition	Measure	Data source
EFP	Ecological footprint	Ecological footprint consumption (Gha per person)	Global Footprint Network https://www.footprintnetwork.org/
GLO	Globalisation	Globalisation index	KOF Swiss Economic Institute https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html

Source: Authors' compilation

across the panel is represented byρ,i represents the lag length, and ε represents the error term.

$$\Delta y_{i,t} = \theta_0\rangle + \rho y_{it-1} + \sum_{j=1}^{\rho_i} \theta_{1i} \Delta y_{i,t-j} + \varepsilon_{i,t} \quad (1)$$

To evaluate stationarity across countries, the DF test was applied [43], and this technique is widely used to determine the stationarity in time series data [44, 45]. In the DF test, the null and alternative hypotheses are considered as time series being non-stationary and time series being stationary, respectively. The following equation demonstrates the general DF equation utilised in this study.

$$y_t = \beta\prime D_t + \lambda y_{t-1} + \sum_{j=1}^{p} \theta_j \Delta y_{t-j} + \varepsilon_t \quad (2)$$

In Eq. 2, D and λ denote the constant and regression coefficient respectively, and ε_t represents the error term. Hypotheses are evaluated at the significance level of 1% for both LLC and DF tests. If the variables are non-stationary, the differencing method is applied up to two levels.

The unit root tests indicate that the variables exhibit non-stationary behaviour in levels but become stationary after first differencing (Refer Additional file 5). While this justifies the use of different series for Granger causality analysis, it is important to note that differencing may remove potential long run equilibrium relationship if the variables are cointegrated. In the absence of a formal panel cointegration testing, the analysis primarily captures short- to medium-term dynamic relationships rather than long run structural associations.

Stability test

The stability of variables is also considered before the Granger causality approach. Regional stability is assessed through the PVAR stability test, and country-wise stability is determined by applying the VAR stability test. Conducting the stability test to identify the optimal lag length is critical. Using the Moment selection Akaike information criteria (MAIC), moment selection Bayesian information criteria (MBIC), and moment selection Hannan and Quinn criteria (MQIC), the optimal lag length for the PVAR test was discovered.

For each country, the optimal lag length structure was selected based on standard information criteria to ensure model consistency.

Panel and country-level Granger causality

This study used the Granger causality approach, first introduced by Granger in 1969 [46], to test the temporal causality between environmental degradation and globalisation at the European and country-levels. The Granger causality approach is a widely used analytical technique across various research disciplines for identifying causal links between study variables. This analytical technique helps predict one variable from the past value of another [41] and demonstrates the directional relationship between variables. For regional causality, the PVAR Granger test and for analysing country causality, the VAR Granger test is adopted.

Equation 3 display the PVAR Granger causality equation used for the PVAR Granger test.

$$Y_{i,t} = \sum_{k=1}^{\rho} \beta_i Y_{i,t-k} + \sum_{k=0}^{\rho} \theta_k X_{i,t-k} + \varepsilon_{it} \quad (3)$$

Y and X represent the dependent and independent variables, while in the equation i and t represent the region and the year, respectively.

The following equation display the VAR Granger causality equation used in this study to test the causality between variables within countries.

$$Y_{i,t} = \sum_{k=1}^{\rho} \overline{\beta}_i Y_{i,t-k} + \sum_{k=0}^{\rho} \pi_k X_{i,t-k} + u_{i,t} \quad (4)$$

In Eq. 4, Y and X act as dependent and independent variables, respectively, representing individual countries. The time in years is denoted by t. In both tests, causality was identified at the 1%, 5%, and 10% significance levels.

While Granger causality provides useful insights into temporal predictability between variables it does not establish structural causations. In a bivariate framework the estimated relationships may be influenced by omitted common drivers such as economic growth, energy consumption, environmental regulation and technological change. Therefore, the results should be interpreted with caution, reflecting predictive linkages rather than the direct causal effect.

Even though multiple country specific Granger causality tests are conducted, there is a possibility of increasing type I error due to multiple testing. Therefore, the results should be interpreted with the caution, particularly when identifying significant relationships across countries.

Wavelet coherence analysis

Wavelet coherence is employed to examine localised co-movements and lead-lag dependence between globalisation and ecological footprint across time and frequency domains. This study adopts the Wavelet Coherence methodology introduced by Goupillaud, Grossmann and Morlet [47].

It is important to note that Wavelet Coherence does not identify causality in the econometric sense; rather, it captures localised co-movement patterns and phase differences across time–frequency space. Accordingly, phase arrows are interpreted as indicators of lead-lag relationships rather than structural causal directions.

This technique has been widely applied across various research fields [44, 45, 48, 49] to analyse time-varying relationships in time-series data. While Granger causality evaluates predictive relationships over the full sample period, wavelet coherence provides insights into how these relationships evolve across different time horizons by decomposing the series into multiple frequency bands. The inclusion of Wavelet Coherence therefore enhances the analysis by capturing time-varying dependence structure. Equation 5 presents the Wavelet Coherence specification applied in this study.

$$\psi^{a,b}(x) = |a|^{-\frac{1}{2}}\psi\left(\frac{x-b}{a}\right) \tag{5}$$

where $\psi^{a,b}$ denotes the Wavelet function, and a and b represent the scale (contraction) and translation parameters, respectively. Wavelet. Wavelet Coherence facilitates an in-depth analysis of how interrelationship between variables evolves across short-, medium-, and long-term horizons.

In this study, environmental degradation measured by ecological footprint, is treated as the first variable, while globalisation, measured by the KOF Globalisation Index, is considered the second variable. The analysis is implemented using R software to visualise the wavelet coherence diagrams.

Although Wavelet Coherence captures co-movements across time and frequency domains, these patterns should not be interpreted as evidence of long-run equilibrium relationships in the absence of formal cointegration analysis.

LJC heatmap visualisation

This study utilises LJC heatmap as a visual analytical tool to summarise Granger causality results across Europe region [50]. This method is a more appropriate way to visualise Granger's results than the table format, as it makes the directionality and significance levels easier to understand [51, 52]. By incorporating the Granger analysis causality values, p values, used lag length, and the optimal lag length, LJC heatmap can be generated.

The following Fig. 2 visualises the methodology flow diagram of this study. It summarises the research process from identifying the research objective to data analysis, through results and discussion.

A key limitation of this study is the use of a bivariate framework, which does not explicitly control for other macroeconomic, energy, and institutional variables. As such, the estimated relationship may partly reflect shared responses to common underlying facts. Then future research may extend this analysis by incorporating multivariate PVAR or panel cointegration approaches with additional control variables as well as method addressing endogeneity.

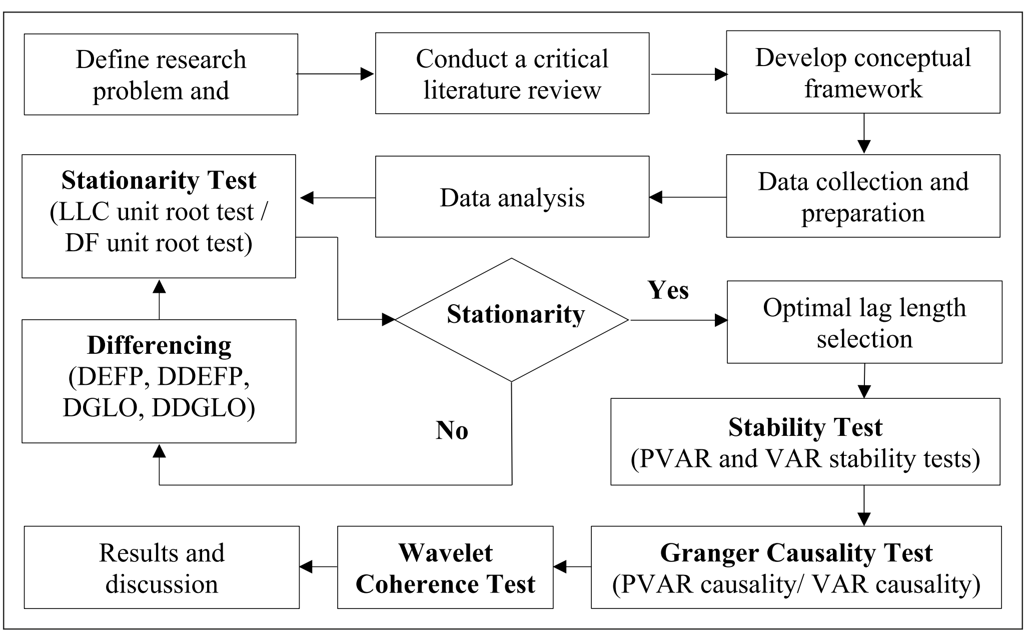


Fig. 2 Methodology flow diagram. *Source*: Authors' illustration

Empirical results

This results section comprises the descriptive analysis, panel-wise Granger results, country-wise Granger results and the Wavelet Coherence results.

Descriptive patterns across Europe

The European map in Fig. 3 shows the mean EFP values across 35 European countries from 1993 to 2023. Accordingly, Luxembourg's consistently high ecological footprint reflects consumption-based environmental accounting, indicating that affluent service economies externalise production emissions, while maintaining high domestic resource demand. Albania recorded the lowest observed EFP value in the European region due to their limited use of carbon and natural resources, including land and water. In Cyprus, Switzerland, the Russian Federation, and the United Kingdom, the same mean EFP value was recorded due to policies and regulations imposed by the regional organisation. Figure 4 shows the mean GLO values for the individual European countries. Influenced by higher social, economic, and political integration over the period, Belgium recorded the highest average GLO value, while the lowest mean GLO value was recorded in Belarus on the European continent. Based on the mean GLO values, most European countries have experienced considerable growth in globalisation during the study period. Moreover, Additional file 4 shows cross-country descriptive statistics.

The heatmap in Fig. 5 illustrates the distribution of ecological footprint consumption values across the 35

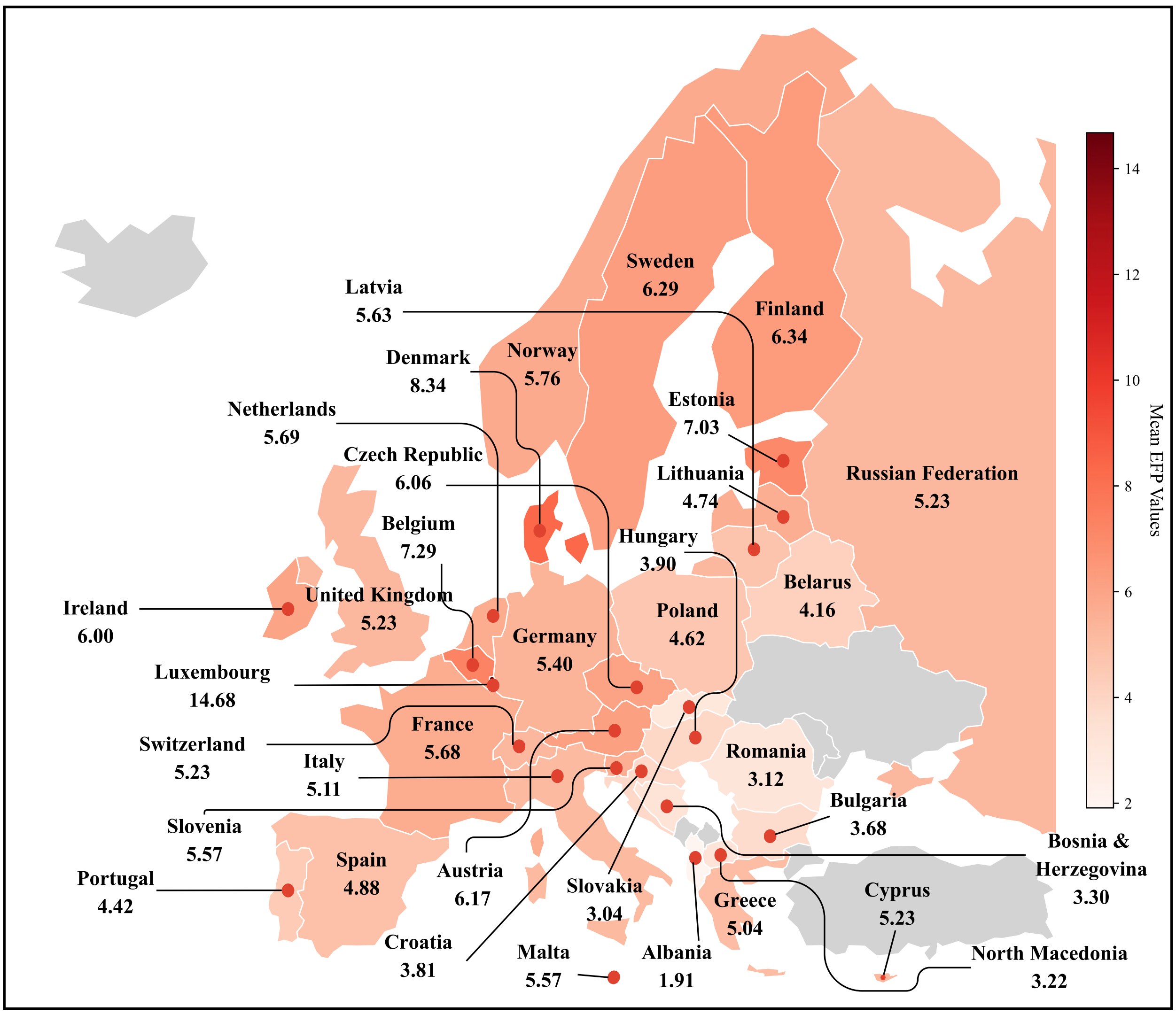


Fig. 3 Mean EFP values across 35 European countries. This figure shows the mean ecological footprint consumption values for individual European countries. High EFP values are shown in dark red colour, and low EFP values are shown in light red colour. *Source*: Authors' illustration

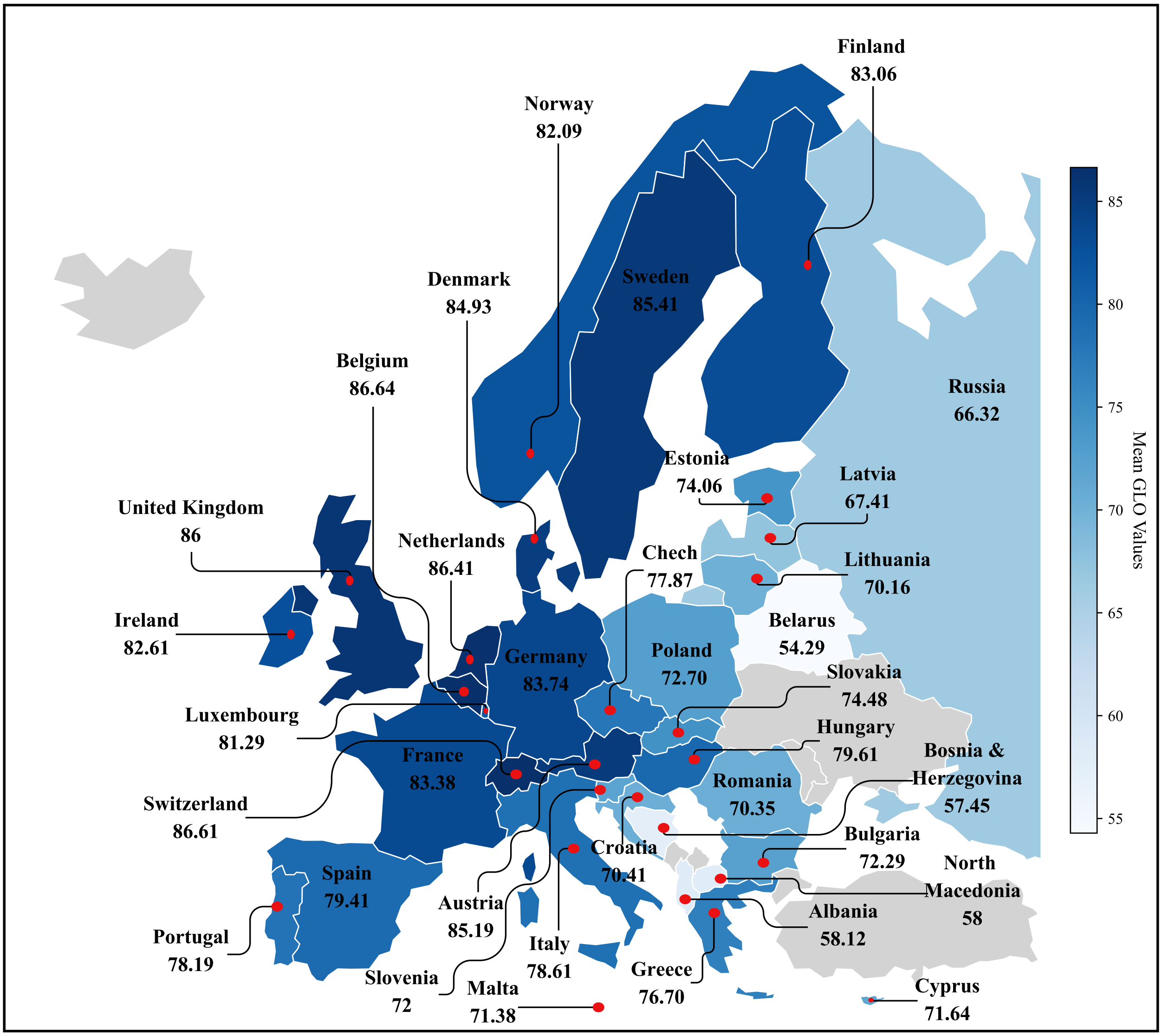


Fig. 4 Mean GLO values across 35 European countries. This figure shows the mean globalisation values for individual European countries. High GLO values are shown in dark blue colour, and low GLO values are shown in light blue colour. *Source*: Authors' illustration

European countries from 1993 to 2023. The demand contractions and structural adjustments following the global financial crisis and the Euro crisis. Due to the financial crisis, the economy has been affected, and manufacturing and production activities have been reduced, because of which the use of carbon and land, the two main factors that significantly affect the ecological footprint, has been significantly reduced [53]. After the European financial crisis, European countries began to show increases in EFP values due to ongoing economic activity. Thereafter, 2019 shows a significant breakthrough, with EFP values again declining for countries due to reduced economic and industrial activity during the COVID-19 pandemic lockdown. Over time, many countries, including Ireland, France and Denmark have displayed steady, consistent growth in EFP, reflecting the implementation of strong sustainable policies.

Panel-level causality results

LLC unit test results for Europe are shown in Table 2. It indicates Europe-wide stationarity of the EFP variable after differencing at the first level. The GLO variable is stationary without differencing.

Lag length selection was conducted prior to stability testing. For the PVAR model, optimal lags were determined using the Moment selection criteria, including the

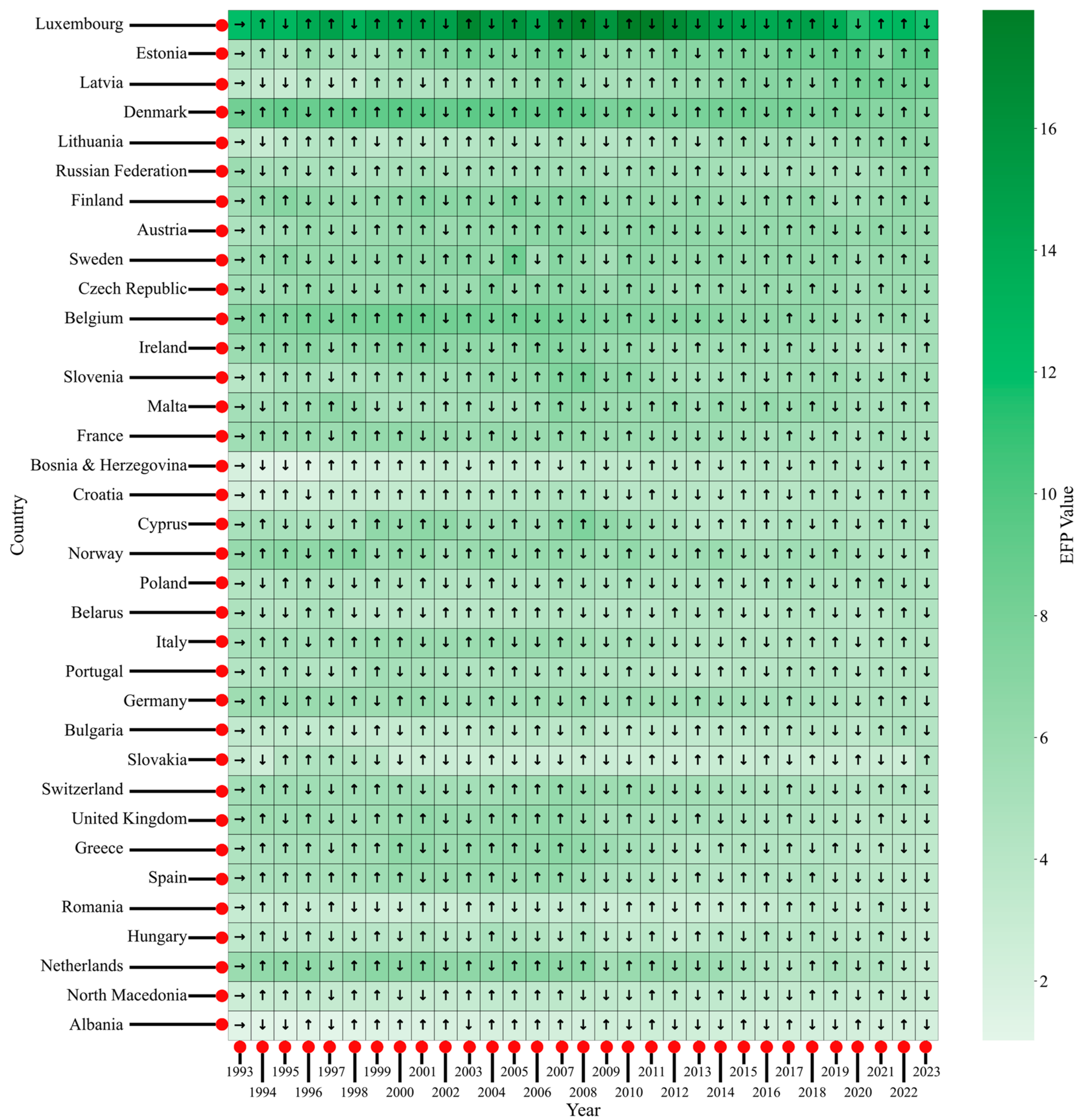


Fig. 5 EFP Distribution across 35 European countries from 1993–2023. (→) No change in the country ranks, (↑) increase the country ranks, (↓) decrease the country ranks. Countries are listed on the vertical axis, while the horizontal axis represents the years. Countries are grouped by the highest EFP value, showing how the ecological footprint differs globally. The colour scale, ranging from light green (low EFP) to dark green (high EFP), reflects each country's level of amplification in environmental pressure over time. *Source*: Authors' illustration based on [7]

Table 2 LLC unit root test results

Region	EFP	DEFP	GLO
Europe	− 0.4417	− 17.8997*	− 13.3244*

Source: Authors' compilation

Moment selection Akaike information criteria (MAIC), moment selection Bayesian information criteria (MBIC), and moment selection Hannan-Quinn criteria (MQIC). For country-level VAR models, standard information criteria-Akaike information criteria (AIC), Schwarz Bayesian information criteria (SBIC), and Hannan-Quinn

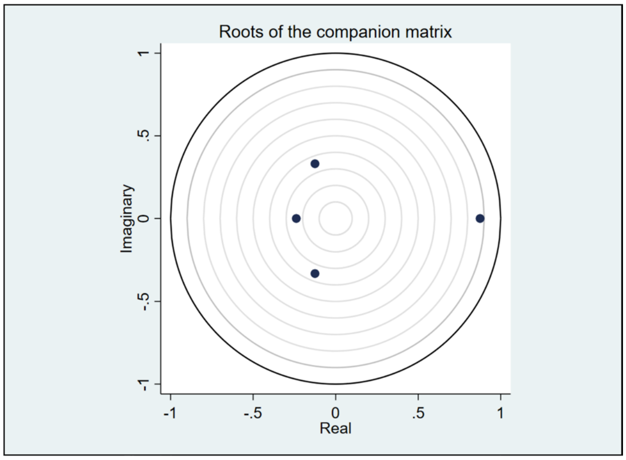


Fig. 6 PVAR stability test for Europe. *Source*: Authors' illustration

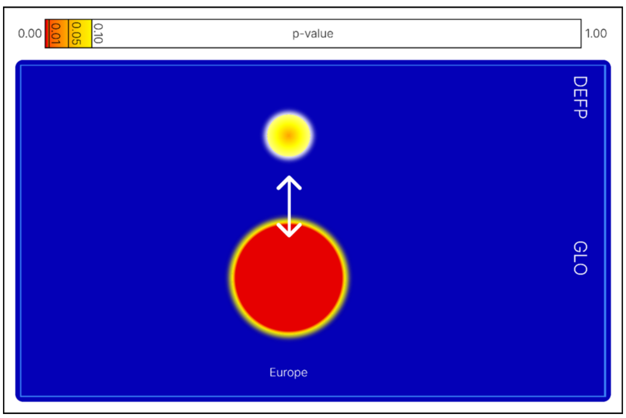


Fig. 7 LJC heatmap for Europe region. *Source*: Authors' illustration

criteria (HQIC) were applied. Based on these criteria, the appropriate lag structures were selected before conducting the regional and cross-country stability tests. Figure 6 presents the regional stability graph.

The LJC heat map in Fig. 7 shows the identified causality between GLO and EFP within the Europe region. According to the panel Granger causality test findings, this study investigates a bidirectional relationship between EFP and GLO, implying that both variables influence each other within the European region. The LJC heatmap is constructed based on p value obtained from region level Granger causality tests. Each cell represents the statistical significant and direction of causality between ecological footprint and globalisation for Europe region and lag structure. The colour intensity reflects the level of statistical significance, while directional patterns distinguish between ecological footprint to globalisation and globalisation to ecological footprint relationships. The visualisation allows for compact relationship of heterogeneous causal patterns across Europe region. Lag length is selected based on standard information criteria (ex; MAIC, MBIC, MQIC) and the heatmap reflects the corresponding optimal lag structure for Europe region. The colour mapping follows the gradient scheme where dark shades indicate stronger statistical significance, while lighter shades represent weaker or insignificance relationships. Compared to standard tabular presentation the heatmap provides an integrated visual summary of directional and statistical patterns, facilitating easier identification of Europe region heterogeneity and dominants trends. LJC heatmap integrates three key dimensions of Granger causality results—statistical significance, directional relationships and lag structure into an unfiled visual representation of the heterogeneous patterns. Table 3 shows the interpretation of LJC heatmap components.

Country-level heterogeneity

To verify the stationarity of variables within the countries, the DF test was used. All countries achieve stationarity of the EFP and GLO variables in first-difference levels. Additional file 5 shows the results of the cross-country unit root analysis.

Through the analysis, this study found a unidirectional relationship from EFP to GLO in Denmark, Poland, Portugal, Spain, and Austria, indicating that environmental policies and regulations influence globalisation. Furthermore, this analysis investigates one-way causality from GLO to EFP in Albania, Belgium, Bosnia and Herzegovina, Germany, the United Kingdom, Belarus, Finland, and the Czech Republic, indicating that Ecological footprints of European nations may be impacted by increasing resource exploitation, altered supply chain architecture, and technological transfer brought on by the globalised economy.

However, according to VAR Granger causality test findings most of the countries in Europe found no Granger causality between GLO and EFP including Bulgaria, Croatia, Estonia, Ireland, Lithuania, North Macedonia, Romania, Russian Federation, Slovenia, Cyprus, France, Greece, Italy, Lativia, Luxembourg, Malta, Netherlands, Norway, Slovakia, Switzerland, Hungary and Sweden, indicating that in these countries neither EFP or GLO influence each other during the time period. These varying directional predictabilities across countries are due to differences in each country's institutional structures, trade structures, industrialisation processes, and environmental regulations. These differences also reflect variations in environmental regulatory stringency, economic structures, and policy enforcement mechanisms across European countries. Country-wise Granger causality analysis results and selected lag lengths for each country

Table 3 Interpretations of LJC heatmap

Names of the symbols		Interpretations
Axis	X axis	Names of the entities
	Y axis	Names of the variables
Arrows	↑ Upward arrow	Unidirectional Granger causality from second variables to first variable
	↓ Downward arrow	Unidirectional Granger causality from first variables to second variable
	↕ Bidirectional arrow	Bidirectional Granger causality between variables
	⇹ Bidirectional arrow cut in the middle	No Granger causality between variables
	Length of the arrow	The longer the arrow, the higher number of lags used in the model
Circles	Top circle	Granger causality from first variable to second variable
	Bottom circle	Granger causality from second variable to first variable
	Warm colours	Results are statistically significant. (Red —1% significance, Orange —5%, Yellow —10% significance)
	Cold colours	The results are not statistically significant. (significance more than 10%)
	Circle size	The higher the circle size, the higher the z-bar tilde statistics value

Source: Authors' compilation

are shown in depth in Additional file 6. Figure 8 summarises the cross-country Granger analysis results. This figure shows the country-wise granger causality results. The circles show the unidirectionality from EFP to GLO, and the square shape shows the unidirectionality from GLO to EFP. The study is represented by the colours yellow (1%), purple (5%), and green (10%) at significant levels, and by the light grey (no causality) and dark grey (not applicable) countries.

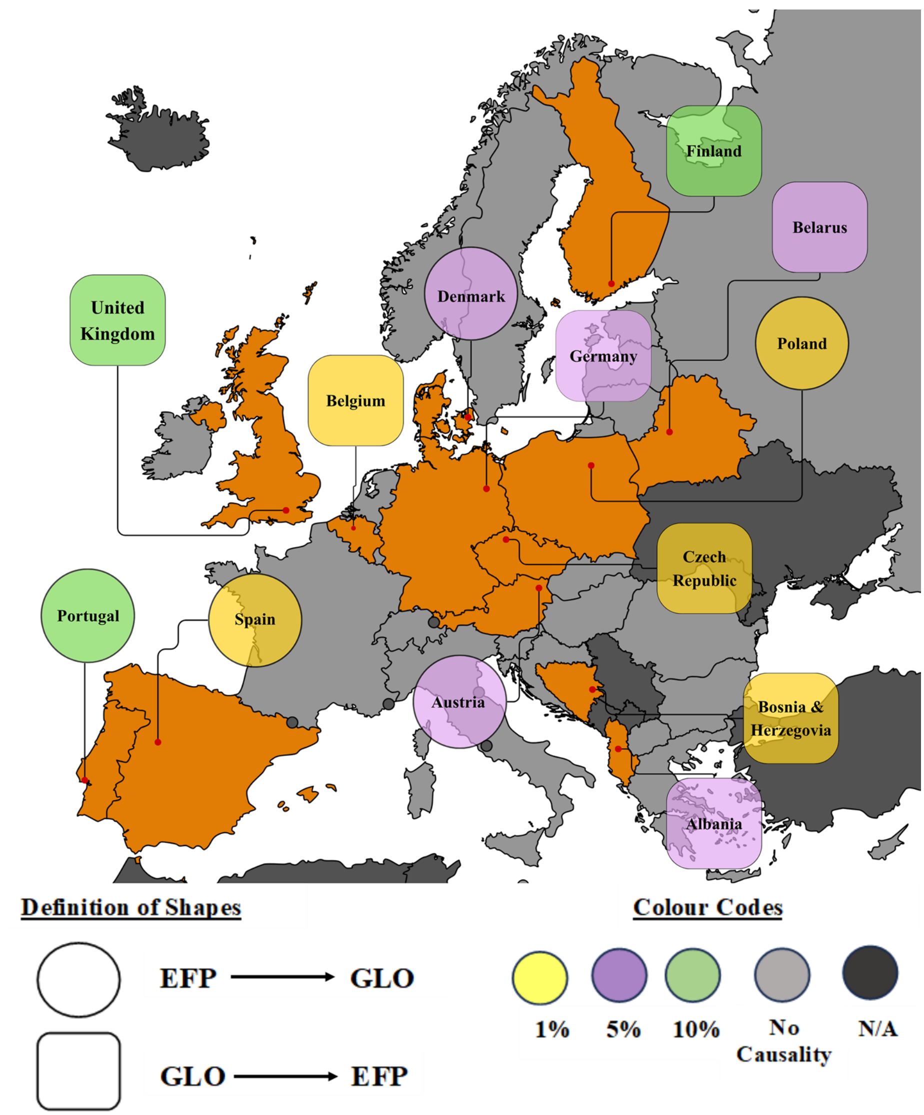
Time frequency dynamics (wavelet results)

By considering EFP as the first variable and GLO as the second, a Wavelet Coherence graph was generated for the Europe region. The 'area of influence', which is the inside part of the grey-shaped cone, is considered in the analysis. The scale ranges from 0 to 256, divided into three-time frames: short-, medium-, and long-term, at 0–16, 16–64, and 64–256, respectively. The direction of arrows shows whether variables move in-phase or out-of-phase. In-phase movements indicate that ecological footprint and globalisation move together positively over a given time frequency region, whereas out-of-phase movements indicate that the two variables move in opposite directions. Phase arrows further suggest which variable leads the other, but such lead-lag movements should not be interpreted as definitive causal evidence. The blue and red colours indicate medium and high frequency. Table 4 presents the interpretation of attributes used to explain and interpret the Wavelet Coherence diagrams. In the present study, the first variable refers to ecological footprint (EFP) and the second variable refers to globalisation (GLO). Accordingly, downward right arrow indicates positive co-movements with the EFP leading GLO, while upward right arrow indicates positive co-movements with GLO leading EFP. Also, upward left arrow indicates negative co-movement with GLO leading EFP, while downward left arrow indicates negative co-movement with EFP leading GLO.

The Wavelet Coherence diagram shown in Fig. 9 demonstrates the time frequency dynamics in the European region between ecological footprint and globalisation.

In the short-term, during 1993–1999, there is a positive correlation and bidirectional relationship in high frequency, indicating that the enhancement in globalisation lead the EFP values, particularly due to the higher demand for trade, energy, industry expansion, and environmental regulation by the introduction of the single market in Europe. During the 2005–2011 period, the GLO variable exhibits mixed correlation, making the EFP variable high-frequency. From 2011 to 2017 and 2017 to 2023, there is a mixed correlation both variables leading each other within a high frequency, suggesting strong lead-lag dependency between variables. From 1999 to 2005, there was no co-movement identified between EFP and GLO during the time scale in the European region.

In the medium-term, a diversified pattern of correlations among variables is observed across various periods. From 1993 to 1999, there is a positive, and strong lead-lag dependency between EFP and GLO at high frequency. From 1999 to 2005, the GLO variable leads the EFP variable in medium-term frequency band, with a mixed correlation. Also, from 2005 to 2011, the same lead-lag dependency was observed, with the GLO variable leading the EFP variable but exhibiting a negative correlation at high frequencies. In the medium-term, from 2011 to 2017, there is a positive correlation; the EFP variable is found leading the GLO variable during that period. Within the last year range (2017–2023), no local correlation was found.



Country-wise granger causality results. This figure shows the country-wise granger causality results. The circles show the unidirectionality from EFP to GLO, and the square shape shows the unidirectionality from GLO to EFP. The study is represented by the colours yellow (1%), purple (5%), and green (10%) at significant levels, and by the light grey (no causality) and dark grey (not applicable) countries.

Fig. 8 Country-wise granger causality results. *Source*: Authors' illustration

In the long-term Wavelet Coherence analysis, the present study identifies that, from 1993 to 1999, EFP variable leads the GLO variable exhibiting in-phase correlation at high frequencies. From 2005 to 2011, 2011–2017, and 2017–2023, similar correlations and lead-lag dependencies have been observed at high frequency. In post-2011 instability, coinciding with structural adjustments following the European sovereign debt crisis, macroeconomic shocks altered global environmental dynamics. During this period, the analysis shows that the GLO and EFP variables move together. Also, no lead-lag dependencies or co-movements are identified from 1999 to 2005. Following Table 5 demonstrates a summary of Wavelet findings for more in-depth understanding.

Robustness consideration

To assess the robustness of the findings, alternative model specifications and measurement considerations were evaluated conceptually. While the KOF Globalisation Index provides a comprehensive measure, future

Table 4 Interpretation of wavelet coherence

Symbol		Description
→	Rightward arrow	In-phase: the two variables move together positively
←	Leftward arrow	Out-of-phase: the two variables moving in opposite directions
↗	Rightward up arrow	In-phase: second variable leads first variable
↘	Rightward down arrow	In-phase: first variable leads second variable
↖	Leftward up arrow	Out-of-phase: second variable leads first variable
↙	Leftward down arrow	Out-of-phase: first variable leads second variable
0–16		Short-term
16–64		Medium-term
64–256		Long-term

Source: Authors' compilation

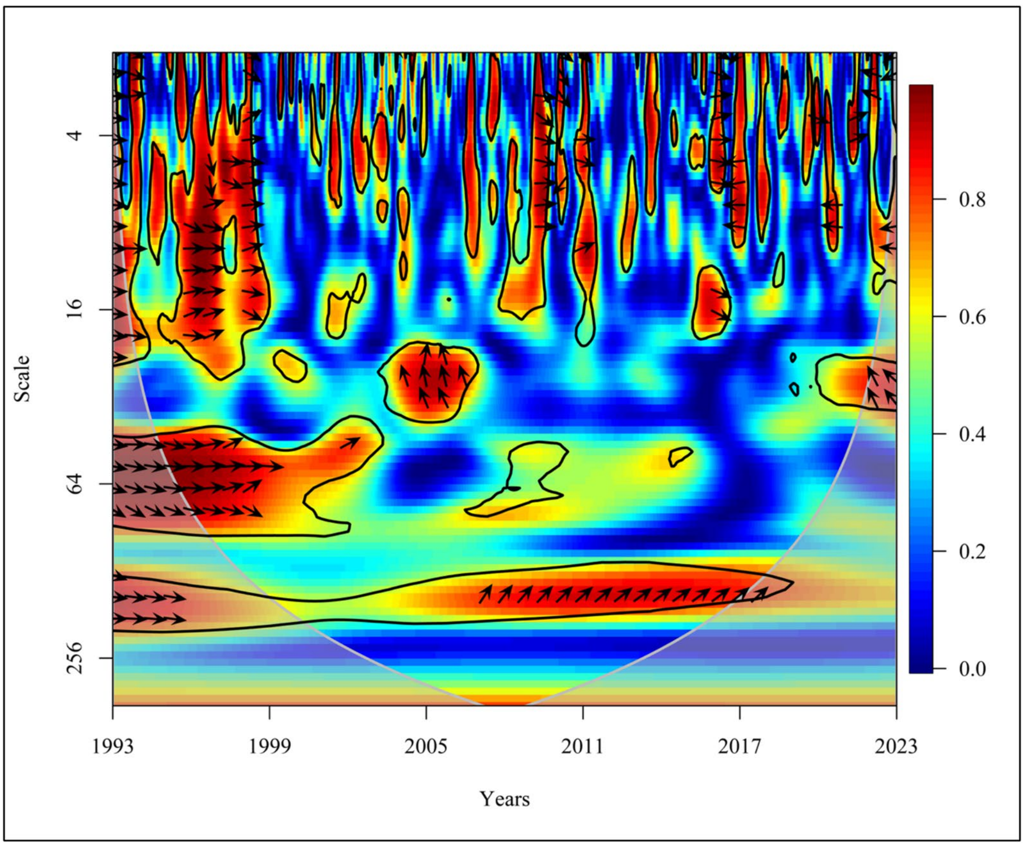


Fig. 9 EFP and GLO wavelet coherence diagram. *Source*: Authors' illustration

research may consider disaggregated sub-indices (economic, social and political globalisation) to examine whether the observed relationship remains consistent across different dimensions. Additionally, sensitivity to sample period selection may be explored by considering sub period analysis, particularly around major economic or policy transitions.

Discussion

This section compares the present analysis outcomes with findings from the existing literature.

Regional level dynamics

Europe's regional analysis establishes a bidirectional causal link between EFP and GLO, reflecting that Europe's environment and globalisation have significant

Table 5 Summary of wavelet findings

Time Period	Short Term	Medium Term	Long Term
	EFP - GLO	EFP - GLO	EFP - GLO
1993 – 1999	+ ↔	+ ↔	+ ↙
1999 – 2005	×	± ↗	×
2005 – 2011	± ↙	− ↗	+ ↗
2011 – 2017	± ↔	+ ↙	+ ↗
2017 – 2023	± ↔	×	+ ↗

Note:

1. Nature of the correlation
   + - Positive − - Negative ± - Mixed
2. Direction of the arrows
   ↘ ↙ - First variable leads the second variable
   ↗ ↖ - Second variable leads the first variable
3. Scale of frequency
   ■ - High ■ - Medium

Source: Authors' compilation

effects on each other. Europe is a highly globalised, industrialised, and trade- and foreign direct investment-focused region. Taken together, these countries' overall effect significantly affects the environment; at the same time, greater environmental degradation enhances globalisation. Past literature presents divergent findings from the present study, providing both bidirectional and unidirectional relationships between environment and globalisation [15, 18]. These numerous findings suggest that, based on environmental indicators, findings can vary even in the same geographical area. Such heterogeneity also suggests that environmental governance frameworks play a critical role in mediating the environmental consequences of globalisation.

The identified bidirectional relationships at the regional level should be interpreted as reflecting interconnected dynamics within broader macroeconomic and institutional systems, rather than direct causal transmissions. In the European context, supernational regulatory frameworks, energy transitions, and economic integration process jointly sharpen both globalisation and environmental outcomes. Therefore, the observed relationship likely captures systemic interactions rather than isolated causes and effect mechanisms.

It is important to note that ecological footprint is a composite indicator comprising multiple components including carbon emission, land use, and resource consumption. These components may respond differently to the globalisation process. For example, globalisation may increase carbon emissions through scale effect while simultaneously improving resource efficiency through technological transfer. As the present study uses the aggregate ecological footprint, such differentiated effects are not explicitly captured.

Country-level heterogeneity

When comparing country-level causality, the present study demonstrates a unidirectional causal effect from GLO to EFP in the UK, emphasising that globalisation initiatives, such as energy consumption, industrial production, and natural resource consumption, can cause environmental changes in the UK [54]. Across different causality approaches, prior literature reports empirical findings consistent with those investigated in the present research [28, 29]. In addition to the similar findings, certain studies analyse a unidirectional relationship from environmental indicators to globalisation in the UK [30]. These multiple results suggest heterogeneity across environmental indicators.

Poland shows a unidirectional causality from EFP to GLO, revealing that Poland's environmental policy and regulatory structure have a directional effect on the globalisation framework. Previous studies in Poland reported a unidirectional relationship from GLO to the load capacity factor [20]. These findings suggest that the influence of GLO on environmental demand for renewable energy, following environmental policies, has a positive impact on biodiversity preservation.

In the present study, Russia finds no directional causality between EFP and GLO variables, indicating limited linkage between them and strong institutional and policy implications that neutralised the relationship. A previous study's analysis confirms that results utilising both Toda-Yamamoto and Fourier Toda-Yamamoto causality tests [4]. These outcomes suggest that, although Russia is a high-income country, it has achieved a sustainable policy structure and a process of globalisation.

This study examines a unidirectional relationship from GLO to EFP in Belgium and one-way causality from EFP to GLO in Portugal, suggesting that countries' institutional quality, economic structures, and energy intensity have different effects on countries' EFP patterns. An analysis of developed nations revealed consistent results regarding Belgium's globalisation-environment nexus, along with findings for Portugal indicating one-way causality from globalisation to the environment [6]. Moreover, the current study demonstrates no directional causality between EFP and GLO. A study developed in the same nation found inconsistent results for these countries.

This investigation finds no directional causality between EFP and GLO in France and Italy, indicating that these countries have no statistically significant association between the variables, thus reflecting that their economic, social, and political initiatives have lower interaction with environmental outcomes. When comparing these with past literature, studies show there is a unidirectional relationship from GLO to $CO_{2,}$ and a bidirectional relationship indicating countries' economic activities increase energy use, green technology practices influence the environmental indicators in these countries, while strong policy regulation also affects the globalisation [27, 30]. These findings can vary based on the analysed environmental indicators, the considered sample size, the time period, and the used methodologies, even within the same geographical area.

The absence of significant causal relationships in many countries may reflect structural and institutional heterogeneity across Europe. Differences in governance quality, industrial structure, energy dependency and environmental policy frameworks can weaken or obscure direct dynamic linkages between globalisation and ecological footprint. In highly regulated and mature economies, environmental outcomes may be influenced by long-term policy frameworks and technological adoption, rather than short-term dynamic interactions captured by the Granger causality. This pattern is consistent with the portion of regional dominance where supernational governance structures and coordinated policy mechanisms within Europe shape environmental outcomes more stronger than country specific dynamics. For instance, countries with higher reliance on renewable energy and strict environmental regulations may exhibit weaker or delayed responses of ecological footprint to globalisation, whereas more industrialised or energy intensive economics may display stronger short-term linkages.

Synthesis of Granger and wavelet results

The key insight of this study emerged from the combined interpretation of Granger causality and Wavelet Coherence results. While the granger analysis identifies strong bidirectional predictive relationships at the regional level, the Wavelet Coherence analysis reveal that these relationships are not uniform overtime but vary across short-medium- and long-term frequency gaps. This suggest that the regional level bidirectional dynamics reflect an aggregation of time variant interactions rather than the stable causal mechanisms.

Furthermore, the absence of consistent country-level causality aligns with the Wavelet findings, which shows fragmented and heterogeneous lead-lag patterns across countries and time horizons. Together these results highlight the importance of adopting multi-scale analytical perspectives to capture complex environmental globalisation dynamics.

Short- and medium-term dynamics

Short-term time–frequency analysis confirms a positive correlation between EFP and GLO. In certain periods, it aligns with the EKC theory, which demonstrates that the early-stage globalisation-enhancement process demands more resources and carbon, leading to greater environmental degradation. These findings are supported by prior literature, which identifies a positive correlation between globalisation and the environment [30]. In the Wavelet Coherence analysis, it was found that long-term globalisation leads to environmental degradation, compared with previous studies. A study based on EU members found that long-term globalisation influences sustainability through economic, human, and infrastructure development [23]. Moreover, in the long term, this study shows a positive correlation between GLO and EFP, whereas a previous study shows a negative correlation between the variables [24]; however, it also found the same causal direction. The dynamic relationship between globalisation and ecological footprint should consider the potential role of long run equilibrium mechanisms which are not explicitly modelled in this study. Therefore, the findings reflect short- to medium-term adjustments and co-movement patterns, rather than confirming long-run equilibrium dynamics.

Theoretical implication

The empirical findings provide nuanced insights into the theoretical expectations of EKC and EMT. The observed short-term lead-lag relationships suggest the presence of scale effects consistent with the early stage of EKC hypothesis, where increased economic activity and global integration intensify environmental pressure. However, the absence of strong and consistent long-term causality combined with evidence of co-movements at broader scales aligns more closely with ecological modernisation theory, which emphasise the role of institutional coordination and technological adoption in shaping environmental outcomes. The analysis found that long-term GLO causes the EFP in Europe to increase positively, which is in conflict with the EKC theory, but a previous study found that long-term GLO causes environmental sustainability to decrease negatively [24]. In the short-term, GLO was found causing the EFP, but in the medium-term GLO was found negatively causing the EFP, which aligns with the EKC theory. This relationship is confirmed by [13] previous analysis. According to existing study findings, it eventually aligns with the EKC theory, but it periodically misaligns with it.

On the other hand, ecological modernisation theory demonstrates that technological advancement can, through institutional restructuring, reduce environmental degradation. The unidirectional relationship from globalisation to the ecological footprint in this study aligns with the EMT theory. According to EMT theory, globalisation can reduce environmental degradation's short-term co-movement by promoting the adoption of green technologies in production and manufacturing facilities [22]. Based on the results, certain time periods demonstrate consistent findings with the EMT theory.

The divergence between theoretical expectation and empirical findings may be attributed to the unique characteristics of the European context where supernational governance structure, environmental regulation and coordinated policy frameworks influence both globalisation and environmental outcomes. This may lead to more complex and indirect relationships than those predicted by traditional theoretical models.

Why Europe is unique

Europe is a highly globalised, industrialised region, and European countries rely heavily on trade and foreign direct investment. As a result of these actions, European countries exhibit high natural resource consumption, energy intensity, and trade policies that directly cause environmental degradation. Moreover, the use of green technology, technological advancement, and strong environmental policies help to mitigate the negative impact of globalisation on the environment.

Environmental governance implications in Europe

Europe's environmental governance framework provides an important institutional context for interpreting the globalisation–environment nexus. Policies such as the European Green Deal, emissions trading schemes, and environmental taxation influence how economic integration affects ecological outcomes. The results of this study suggest that regional environmental governance plays a significant role in shaping environmental sustainability, highlighting the need for coordinated regulatory strategies across European countries.

By integrating multi-scale empirical analysis with established theoretical frameworks, this study contributes to the literature by demonstrating that the globalisation-environment nexus in Europe is shaped by complex interactions that extend beyond traditional EKC interpretations highlighting the relevance of institutional and systemic perspectives.

A key contribution of this study is the identification of 'regional dominance' where strong bidirectional relationships are observed at the aggregate European level, though by country-level relationships remain largely insignificant. These findings suggest that environmental-globalisation dynamics are shaped by supernational institutional frameworks rather than solely national level mechanisms. Within the context of the Environmental Kuznets Curve this implies that environmental transitions may occur collectively at the regional level through shared policy frameworks. Similarly, from the perspective of ecological modernisation theory, the results highlight the role of coordinated institutional and technological systemic driving sustainability outcomes.

Policy implications

The findings suggest that globalisation and environmental pressure are mostly interconnected within the broader economic and institutional system. Therefore, policy interventions should adopt an integrated approach considering macroeconomic conditions, energy transitions, and regulatory frameworks simultaneously. These policy implications are provided to align with the United Nations Sustainable Development Goals, SDG 6: clean water and sanitation, SDG 12: responsible consumption and production, and SDG 13: climate action.

Implications for bidirectional causality

In the overall Europe region, a mutual interconnection between globalisation and environmental degradation is identified. Therefore, it is important for the Europe region to consider about policies related to global integration and environmental sustainability. The European Union and the United Nations should work together as a region to implement the policies they have developed. In particular, strengthening EU-wide environmental regulatory mechanisms such as carbon pricing, environmental taxation, and cross-border sustainability standards could help mitigate the environmental pressures associated with globalisation. Also, to achieve that, policies should focus on implementing green technology transfer and incentives to support renewable energy, as well as tax credits or grants for cleaner production.

Policy strategies for environmental degradation to globalisation countries

To achieve the sustainable development in the European region, every individual country's attention should be placed towards global integration and environmental quality. Countries like Albania, Belgium, Bosnia and Herzegovina, Germany, the United Kingdom, Belarus, Finland, and the Czech Republic, which have temporal causality from environmental degradation to globalisation, should take actions that enhance globalisation while maintaining environmental quality standards. To achieve those goals, the government should focus on implementing green agricultural systems that enhance globalisation and preserve environmental quality. Particularly, Bosnia and Herzegovina face significant environmental crisis as a consequence of air, water pollution, poor mechanisms for waste management, and high dependence on coal consumption, which lead to premature deaths. Therefore, they should shift for renewable energy consumption and strengthen environmental qualities to encourage industries to adopt proper waste management strategies. As a European country, Belarus poses a notable threat to the environment, especially through radioactive pollution which occupies a significant place in environmental damage. Therefore, the main solution to reduce the radioactive threat is to control land and soil pollution, promote better control mechanisms for agricultural activities and encouragement to move for green houses. Also, the government should adopt green technologies to promote globalisation and maintain sustainable environmental quality.

Policy strategies for globalisation to environmental degradation countries

Denmark, Poland, Portugal, Spain, and Austria exhibit dynamic predictive causal relationships from globalisation to environmental degradation. Those nations should focus on policies to reduce the environmental damage caused by globalisation actions. Aligning with SDG 6: clean water and sanitation to protect the water resource, Portugal needs to apply waste management policies to reduce the level of waste dropped into water resources and protect the biodiversity. As a highly globalised country, Spain can provide tax relief for organisations, industries, and individuals that move away from higher carbon emissions and reduce natural resource consumption; introduce new taxes for industries or organisations that do not move from higher to lower carbon emissions. Furthermore, countries like Luxembourg which offer free public transport services, can encourage the use of electric vehicles rather than fuel-consuming vehicles and promote the use of public transport services to reduce carbon use in them. By aligning with these policies, these nations can reduce carbon emissions and resource consumption to achieve the SDG 12: responsible consumption and production and SDG 13: climate action.

Conclusion

Key findings of the contributions

This study investigated a bidirectional relationship in Europe between EFP and GLO. In country-wise analysis, most countries show no significant causality between these variables and not a single country shows bidirectionality. Among the remaining countries, most show a unidirectional relationship from GLO to EFP, while a few show a unidirectional relationship from EFP to GLO.

Limitations

This study also has certain limitations. Some countries were excluded from the analysis due to substantial missing data. This study only discusses the overall globalisation index. Owing to the unavailability of data in terms of the globalisation variable, this study includes only data up to 2023. A key limitation of the study is the absence of formal panel cointegration testing and error correction modelling. If ecological footprint and globalisation are cointegrated, differencing may eliminate long run equilibrium information. Therefore, the results should be interpreted with the caution, particularly in relation to long run dynamics. In-phase difference interpretation in Wavelet Coherence is sensitive to smoothing choice, edge effects and local noise. Therefore, these findings are interpreted as indicative lead-lag patterns rather than definitive causal relationships.

Direction for further research

Future researchers should consider including data from recent years in the analysis. Also, future researchers should consider incorporating variables that affect environmental degradation, such as urbanisation, climate, natural factors, economic factors, and the quality of institutions. Overall, these findings suggest that European environmental outcomes are influenced less by national policy alone, than by broader globalisation dynamics operating within a highly integrated regional context, highlighting the importance of coordinated supranational sustainability strategies. Therefore, coordinated regional environmental governance and regulatory harmonisation across Europe are essential to balance global economic integration with ecological sustainability.

Further research may incorporate panel VAR/PVAR framework with error corrections to better capture long run relationships. Alternative approaches such as panel cointegration tests (e.g., Westerlund, CCE estimator, or Dumitrescu-Hurlin causality test), formal multiple testing corrections such as false discovery rate adjustments, and robustness testing across alternative lag specification to strengthen country-level inference may provide further robustness in future research. Although additional robustness checks such as alternative globalisation measures and sub-sample analysis are beyond the scope of this study, they represent important avenues for future research. Future research may also disaggregate the ecological footprint into it constitute components to examine how different dimensions of environment pressure respond to globalisation across countries.

Supplementary Information

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Additional file 1.
Additional file 2.
Additional file 3.
Additional file 4.
Additional file 5.
Additional file 6.

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Author contributions
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